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# ON THE POSSIBILITY OF MILLIMETRE-WAVE AMPLIFICATION WITH AN X-BAND LSA OSCILLATOR

B. Majborn

**Introduction.** Theoretical considerations [1] as well as experimental results [2] indicate that, during oscillation, an LSA oscillator viewed as a lumped circuit element exhibits a negative conductance at frequencies from dc to approximately  $f_0/Q_d$ , where  $f_0$  is the LSA oscillation frequency and  $Q_d$  is the differential Q of the LSA resonant circuit, whereas for higher frequencies the conductance is positive.

However, for signal frequencies considerably higher than the LSA oscillation frequency, the signal wavelength may be of the same order of magnitude as the length of the LSA oscillator in the direction of signal propagation, so a new analysis is needed taking into account the distributed nature of the oscillator as seen by the signal.

In the small-signal approximation, an LSA oscillator (or a sample of n-type gallium arsenide externally pumped under limited space-charge accumulation conditions) may be viewed as an anisotropic medium of time-varying conductivity. The conductivity in the direction of the bias field is negative during part of the oscillation period (pump period), and positive during the rest of the period. As a necessary condition for the control of space-charge growth during a whole pump cycle the average differential conductivity must be positive [1]. Nevertheless, an electromagnetic wave, which travels through a pumped gallium arsenide sample with the electric field vector parallel to the bias field, may be amplified, if the travelling-length during the part of the pump period when the conductivity is negative is considerably longer than the travelling-length during the rest of the period. This condition may be met in LSA operation, where the major part of the cycle is spent in the region of negative differential conductivity.

A simple one-dimensional analysis of small-signal wave propagation through a pumped gallium arsenide sample has been carried out. The results to be reported in the following will demonstrate the possibility of two-port amplification for samples longer than about a quarter of a wave-length at the signal frequency.

**Model.** The geometry considered is schematically illustrated in fig. 1a. A sample of n-type gallium arsenide is assumed to oscillate in the LSA mode (self-oscillating or externally pumped) with the bias field in the y-direction. The pump field is assumed to be uniform across the whole sample and to impart to the sample a time-varying small-signal conductivity in the y-direction.

The injected electromagnetic signal-wave is assumed to travel in the z-direction with the electric field in the y-direction. The amplitude of the signal-wave is assumed to be much smaller than the pump amplitude, so that the sample properties may be derived from the pump field alone.

The problem is assumed to be one-dimensional, i.e. the signal field is assumed to be a function of time and the coordinate z only. The sample length in the z-direction is then the only geometrical parameter.

The pumped sample is simulated by a transmission-line model with constant distributed series inductance, L, and shunt capacitance, C, and with time-varying distributed shunt conductance, G(t). The assumed model is sketched in fig. 1b. A segment of the transmission-line represents a small

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fraction of length  $\Delta x$  of the corresponding sample, so, assuming a unit cross-section area perpendicular to the direction of signal-wave propagation,  $L$ ,  $C$ , and  $G(t)$  are determined by:

$$L = \mu \cdot \Delta x, \quad C = \epsilon \cdot \Delta x, \quad \text{and} \quad G(t) = q \cdot n \cdot dv/dE(t) \cdot \Delta x,$$

where  $\mu$  is the permeability,  $\epsilon$  is the real part of the permittivity (which is assumed constant),  $q$  is the electronic charge,  $n$  is the free carrier concentration (which is assumed equal to  $n_0$ , the homogeneous concentration of donor atoms) and  $dv/dE(t)$  is determined from the analytical expression [3].

$$v(E) = (u_0 E + v_s (E/E_n)^4 / (1 + (E/E_n)^4)),$$

where  $E_n = 4000$  V/cm,  $v_s = 8.5 \times 10^6$  cm/s,  $u_0 = 8000$  cm<sup>2</sup>/V·s, and  $E = E(t) = E_0 - E_0^n \cos \omega_p t$  is the pump field.

The transmission-line is assumed to be fed by the source voltage  $V \sin(\omega t + \phi_s)$ , and the boundary conditions for the sample are simulated by the source impedance,  $Z_s$ , and the load impedance,  $Z_l$ .  $Z_s$  and  $Z_l$  may be chosen arbitrarily corresponding to various circuit configurations.

From the transmission-line equations and the equations expressing the boundary conditions at the source and at the load, the voltage and current distributions along the transmission-line may then be computed at any time when the initial conditions are specified.

The assumption of a uniform pump field restricts the maximum sample length in the direction of signal-wave propagation to about  $(1/8)\lambda_p$ , where  $\lambda_p$  is the wavelength in the sample material at the pump frequency [4]. This restriction does not necessarily mean that amplification is not possible for samples longer than about  $(1/8)\lambda_p$ . However, for greater sample lengths wave-propagation at the pump frequency should be included in the analysis.

**Results.** The results to be reported here corresponds to  $Z_s$  and  $Z_l$  both equal to the characteristic impedance of the lossless transmission-line obtained for  $G(t) = 0$ . A sinusoidal driving voltage is applied to the input of the line for  $t \geq 0$ , with the initial condition that the voltage is zero at all mesh points for  $t < 0$ .

The parameters used in the computations are:

- $E_0$  = dc bias field
- $E_0^o$  = LSA oscillation amplitude (pump amplitude)
- $n_0^p$  = concentration of donor atoms (assumed homogeneous)
- $f_0^o$  = LSA oscillation frequency (pump frequency)
- $f_s^p$  = signal frequency
- $\phi_s$  = initial phase of signal voltage
- $l$  = sample length in the direction of signal-wave propagation.

Fig. 2 shows the first three cycles of the computed output waveform (lower frame). The amplitude 1 corresponds to 0 dB gain. The parameters are given in the figure caption. The upper frame shows the corresponding electric field across the sample (pump field) and the middle frame shows the corresponding differential mobility. The waveform is stationary already from the second cycle.

Fig. 3 shows the corresponding frequency spectrum obtained using the Cooley-Tukey Fourier Transform [5]. The gain at the signal frequency is 0.3 dB, and the sidebands are more than 15 dB below the signal.

Fig. 4 shows the gain at the signal frequency as a function of sample length for  $f_p = 8$  GHz,  $f_s = 64$  GHz,  $\phi_s = 0^\circ$  and

- a)  $n/f_p = 2.5 \times 10^4$  s/cm<sup>3</sup>,  $E_0 = 7$  kV/cm,  $E_p = 4.8$  kV/cm
- b)  $n/f_p = 5 \times 10^4$  s/cm<sup>3</sup>,  $E_0 = 10$  kV/cm,  $E_p = 8$  kV/cm

$$c) \quad n/f_p = 1 \times 10^5 \text{ s/cm}^3 \quad E_o = 20 \text{ kV/cm} \quad E_p = 18 \text{ kV/cm}$$

The highest gain obtained for these parameters is 1.4 dB for  $f_p = 1 \times 10^5 \text{ s/cm}^3$  and  $l = (3/4)\lambda_s = 0.993 \text{ mm}$ . Because of the choice of source and load impedances the matching of the sample becomes poorer and poorer as  $G(t)$  is increased. For  $n/f_p = 5 \times 10^4 \text{ s/cm}^3$  and  $f_s = 64 \text{ GHz}$  the maximum value of  $G(t)$  is approximately equal to  $\omega C$ .

The variation of gain with the phase of the injected signal relative to the phase of the pump field has been computed for  $f_s = 16 \text{ GHz}$ ,  $f_p = 32 \text{ GHz}$  and  $f_p = 64 \text{ GHz}$ . The variation is only marked at the lower signal frequencies.<sup>s</sup> For a sample length of  $1.325 \text{ mm} = (1/8)\lambda_p$  and  $n/f_p = 5 \times 10^4 \text{ s/cm}^3$  the gain at  $f_s = 16 \text{ GHz}$  varies between 2.6 dB and 1.3 dB for  $-\pi/2 \leq \phi \leq \pi/2$ , whereas the gain variation at  $f_s = 32 \text{ GHz}$  is between 1.4 dB and 1.0 dB. At  $f_s = 64 \text{ GHz}$  the gain is independent of  $\phi_s$  and equal to 1.0 dB.

**Discussion.** The results reported in the preceding section have demonstrated that theoretically an LSA oscillator or an externally pumped sample of n-type gallium arsenide may be used as an amplifier of small signals at frequencies well above the oscillation frequency. This amplification property arises from the possibility of a net spatial growth of an electromagnetic wave which travels through the oscillating sample.

The results demonstrate, however, that, under the loading conditions considered so far, only moderate gains are obtained. Higher gains may be obtained by choosing more optimal parameters, but the obtainable gain with a single pumped sample used as a transmission amplifier will be rather limited, due to the basic limitations on carrier concentration and sample length (perpendicular to the bias field) relevant to the LSA mode.

Therefore it is suggested that a practical amplifier based on the time-varying small-signal conductivity exhibited by an LSA oscillator should consist of a number of properly phased LSA oscillators in series, or be based on multiple reflections in the pumped sample when placed in a cavity of proper dimensions. These possibilities will be further investigated.

By loading the sample with a resonant circuit tuned to one of the sideband frequencies, a converter is obtained. The conversion properties of the LSA oscillator will be further investigated as well.

The proposed amplifier is not subject to transit-time limitations, so it may be possible to design practical amplifiers for use at high millimetre-wave frequencies. The maximum bandwidth is equal to the LSA oscillation frequency.

In the present theory space-charge effects have been neglected. It may be a requirement for experimental verification that high quality gallium arsenide with a flat doping profile is available.

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#### References.

- 1 J.A. Copeland, J.Appl.Phys., 1967, 38, pp. 3096-3101.
- 2 R.R. Spiwak, IEEE Trans.Electron Devices, 1968, ED-15, pp. 614-615.
- 3 H.W. Thim, J.Appl.Phys., 1968, 39, pp. 3897-3904.
- 4 J.A. Copeland, IEEE Trans.Electron Devices, 1967, ED-14, pp. 497-500.
- 5 N.M. Bremer, Lincoln Laboratory, 1967, Tech.Note 1967-2.

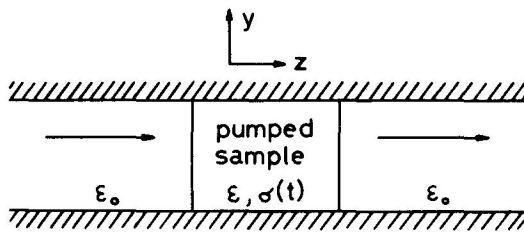


Fig.1a. Schematic illustration of the assumed geometry.

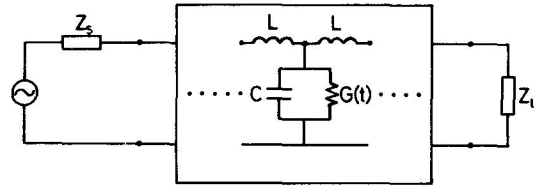


Fig.1b. The transmission-line model.

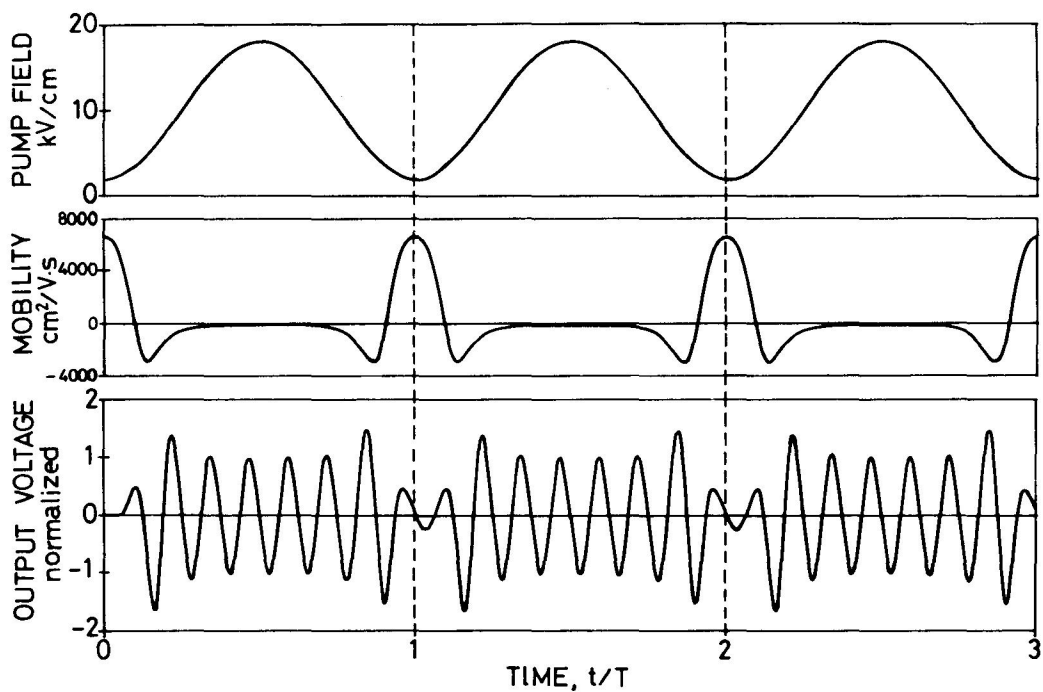


Fig.2. Pump field (upper frame), mobility (middle frame) and normalized output voltage (lower frame) versus time for the first three pump cycles.  $E = 10\text{ kV/cm}$ ,  $E_p = 8\text{ kV/cm}$ ,  $f = 8\text{ GHz}$ ,  $n/f_p = 5 \times 10^4\text{ s/cm}^3$ ,  $f_s = 64\text{ GHz}$ ,  $\varphi_s = 0^\circ$ ,  $l = 0.5\lambda_s = 0.665\text{ mm}$ .

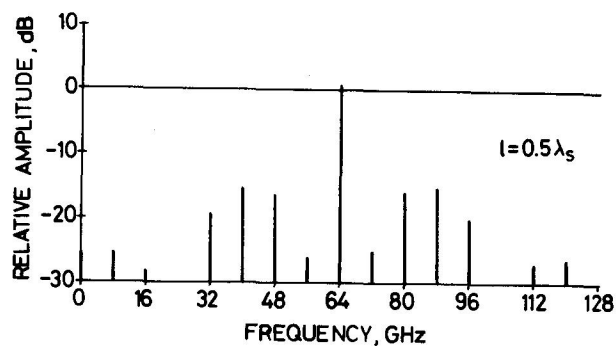


Fig.3. Frequency spectrum corresponding to the output waveform shown in Fig.2.

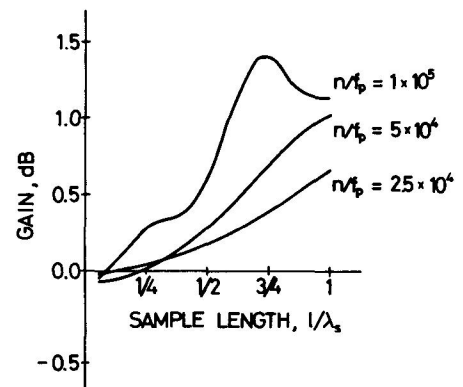


Fig.4. Gain at the signal frequency versus sample length.